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# Simulation System Engineering for Train Operation Based on Cellular Automaton

SU Hongsheng[a], CAI Jing[b*], HUANG Shiming[a,b]

*School of Automation and Electrical Engineering, Lanzhou Jiaotong University, Lanzhou ,730070, China*

**Abstract**

In order to simulate operating characteristics of trains better in different block conditions, three kinds of models are proposed on the train motion under different signaling systems based on cellular automaton(CA) model in this paper, i.e., the train motion behavior under the fixed block, the moving-like block and the moving block conditions. Using the proposed engineering models, we analyze trajectories and space-time diagrams of railway traffic flow, calculate and compare the minimum departure interval under different conditions, and discuss the effect of the proportion and the departure sequence of different trains on mixed traffic flow. The simulation results show that the minimum headway time and the run time of moving block system are shortest, and with the low proportion of slow trains and suitable departure sequence the average run time of trains will be shorten greatly. It corresponds with dynamic characteristics of actual train flow and demonstrates that this system engineering is effective to simulate train movement, and can provide reference for organizations.



*Keywords:* cellular automaton; train movement; signal control system; simulation;

## 1. Introduction

The train control system plays a key role in railway traffic, so it’s significant to establish the simulation system for train operation. Early there are many models based on classical mathematical methods and because of the nonlinear characteristics and rigorous condition of equations the solution is so complex.

The CA models with simple algorithm have been widely used in the study of traffic flow because of its unique advantages. In 1986 the first CA model was proposed by Cremer and Ludwig [1]. One of the most famous CA models for traffic flow was proposed by Nagel and Schreckenberg in 1992 [2]. Li KePing and Gao ZiYou firstly applied the NS model in railway system. Then some scholars proposed models based on cellular automaton to simulate train movement under different signaling systems to describe train operating characteristics. But now many of CA models of rail transit ignore collinear trains with multi-speed, train length, pulling rate, braking rate, line parameters, fault and other practical factors [3-5].

* Corresponding author. Tel.:86-13919316020.
*E-mail address*: caijing-kid@163.com .

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## 2. Modeling

Based on the NS model, the single railway line is divided into L cells remembered by i= 1, 2, ··L and the time is discrete. Each site can be either empty or occupied by one train with integer speed $v_n$=0, 1, ··· $v_{\max}$. Parameter a and parameter b are respectively acceleration rate and deceleration rate. $x_n$ represents the site of the train. Then according to the principles of different signaling control systems we modify the rules of the proposed models [6-10].

### *2.1. CA model of fixed block system*

The railway line under the fixed block condition is divided into several block sections and there is the signal light at the entrance of each block section. The train movement is strongly related to the colors of signal lights in front of it. The principle is shown as figure1.Three speed-limiting functions are as table1and update rules are as table2:

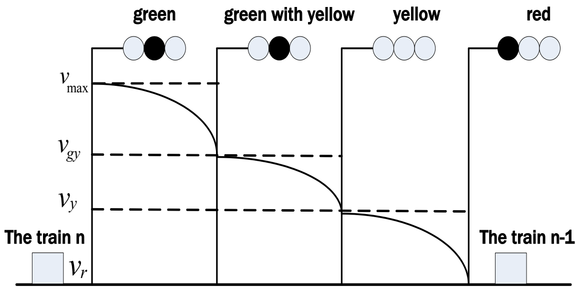



Fig. 1. fixed block system

Table 1. Speed-limiting function

| The color of lights | Green with yellow light | Yellow light | Red light |
|---|---|---|---|
| The function of lights | $v_{gy}(s) = \mathrm{int}(\min(\sqrt{2bs + v_{gl}^2}, v_{\max}))$ | $v_y(s) = \mathrm{int}(\min(\sqrt{2bs + v_{yl}^2}, v_{gl}))$ | $v_r(s) = \mathrm{int}(\min(\sqrt{2bs}, v_{yl}))$ |

Table 2. Update rules of fixed block system

| | Velocity | | Site |
|---|---|---|---|
| Green light | $v_n = \min(v_n + a, v_{\max})$ | | $x_n = x_n + v_n$ |
| Green with yellow light | Fast train | $v_n = \min(v_n + a_q, v_{gy}(s))$ | $x_n = x_n + v_n$ |
| | Slow train | $v_n = \min(v_n + a_s, v_{\max})$ | |
| Yellow light | $v_n = \min(v_n + a, v_y(s))$ | | $x_n = x_n + v_n$ |
| Red light | $v_n = \min(v_n + a, v_r(s))$ | | $x_n = x_n + v_n$ |
| Arrive at station | $v_n = \min(v_n + a, \mathrm{int}(\sqrt{2bs}))$ | | $x_n = x_n + v_n$ |

Where $v_{yl}$ is the limited speed of yellow light and $v_{gl}$ is the limited speed of green with yellow light. s is the distance from the train n to the closest signal light in front of it.

### *2.2. CA model of moving-like block system*

The train movement under the moving-like block is strongly related to its speed control curve. The principle is shown as figure 2 and the update rules as table3:

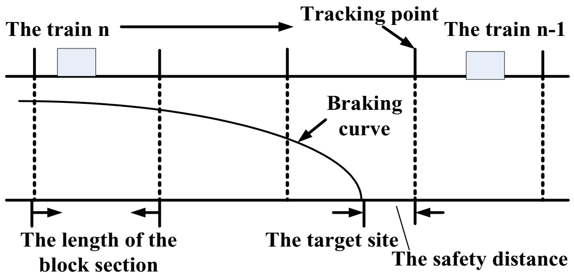



Fig. 2. moving-like block system

Table 3. Update rules of moving-like block system

| Case | $s > d_s$ | $s < d_s$ | $s = d_s$ |
|---|---|---|---|
| Velocity | $v_n = \min(v_n + a, v_{\max})$ | $v_n = \min(v_n + a, \mathrm{int}(\sqrt{2bs}))$ | $v_n = v_n$ |
| Site | $x_n = x_n + v_n$ | $x_n = x_n + v_n$ | $x_n = x_n + v_n$ |

Where s is the distance from the train n to the target site in front of it and $d_s$ is taken as:

$$d_s = v_{max}^2/2b \tag{1}$$

### *2.3. CA model of moving block system*

Under the moving block condition the train completes real-time computation of its speed control curve with the moving target site [11,12]. The principle is shown as figure 3 and this paper adopts MSB mode. In this mode the minimum safety stopping distance is taken as:

$$d_n = v_{max}^2/2b + s_m \tag{2}$$

where $s_m$ is the safety distance. Then we define the update rules as table4

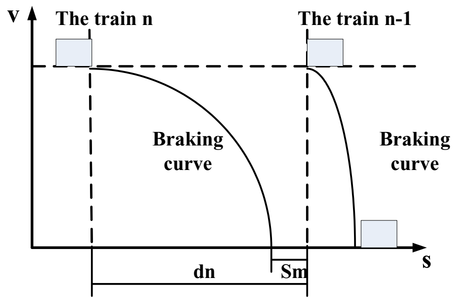



Fig. 3. moving block system

Table 4. Update rules of moving block system

| | Case | Velocity | | Site |
|---|---|---|---|---|
| Train is not at station, or the closest station is occupied by train. | $d > d_n$ | $v_n = \min(v_n + a, v_{\max})$ | | $x_n = x_n + v_n$ |
| | $d < d_n$ | $v_n = \min(v_n + a, \text{int}(\sqrt{2bd}))$ | | |
| | $d = d_n$ | $v_n = v_n$ | | |
| | Braking | $v_n = \min(v_n, gap)$ | | |
| The closest station is empty. | $d_s > x_c$ | $v_n = \min(v_n + a, v_{\max})$ | | $x_n = x_n + v_n$ |
| | $d_s < x_c$ | $v_n = \max(v_n + a, \text{int}(\sqrt{2bd_s}))$ | | |
| | $d_s = x_c$ | $v_n = v_n$ | | |
| Train is at station. | $t_{stop} > T_d$ , $d > L_S$ | $v_n = v_n + a$ | $t_{stop} = 0$ | $x_n = x_n + v_n$ |
| | $t_{stop} \le T_d$ | $v_n = 0$ | $t_{stop} = t_{stop} + 1$ | |

Where $d$ and $gap$ are respectively the distance and the number of empty cells from the train n to the leading train n-1. $d_s$ is the distance from the train n to the closest station and $x_c$ is taken as function (3), $t_{stop}$ and $T_d$ are respectively the actual dwell time and the planned dwell time. $L_S$ is the protection distance.

$$x_c = v_n^2 / 2b \quad (3)$$

## 3. Realizing of simulation system

### 3.1. The design process of simulation system

According to the models and algorithms above, we build the simulation system for the train operation based on the CA model by VC++6.0 and the design process is shown in figure 4:

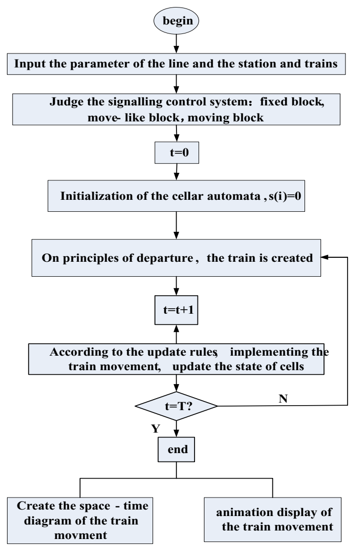



Fig. 4. diagram of design process

### 3.2. Numerical simulation results

A system of L=25000 cells is considered and the station is designed at the 12000th site. All trains should stop at the station for 80s and then leave. Train length is 200cells, the maximum speed of fast train is 40cells/s and slow train is 20cells/s. If one cellular automation iteration is set to be 1s and the cell length is 1m, then the maximum speeds correspond to 144 km/h and 72km/h. The acceleration rate and the deceleration rate of trains are taken 1cell/s$^2$ .The limited speeds are respectively taken 30cells/s and 20cells/s. The block length is 1000 cells.

#### 3.2.1. The analysis of the space-time diagram of trains

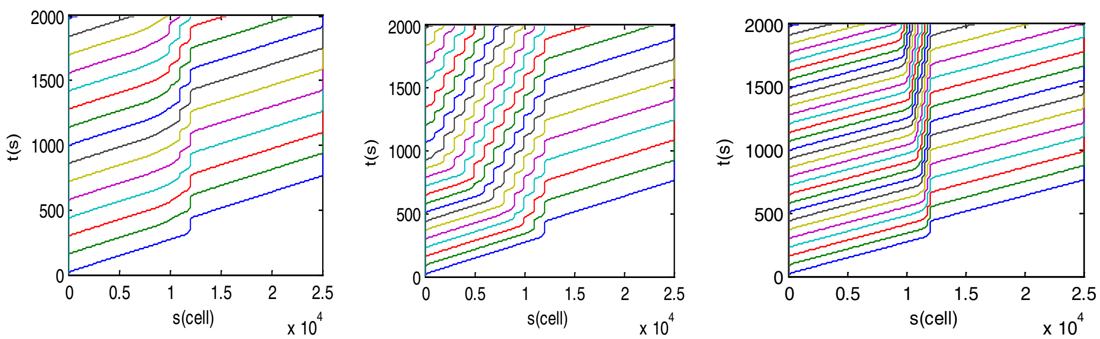



Fig. 5. (a) space-time diagram of fixed block system; (b) space-time diagram of moving-like block system; (c) space-time diagram of moving block system

Figure 5(a), 5(b), and 5(c) are respectively the space-time diagrams under different signaling control systems with the departure time interval of 70s. After 2000 time steps, there are 14 trains under the fixed block condition, 20 trains under the moving-like block condition and 28 trains under the moving block condition. It demonstrates that the efficiency of moving block system is highest and the density is the largest. Because the departure interval is so small that there are more and more trains on the line, tracked trains are influenced by the leading trains and can't run at full speed so that the train delays possibly form and propagate backward. From them, it can be clearly seen that as the time proceeds, a number of trains before the station are delayed. In figure 5(b) we can see that the departure interval increases under moving-like block condition at 1000th time step. That is because there are many trains stopping in front of the departure station and in order to maintain the safe distance it is restricted by the departure signal.

*3.2.2. The calculation of the minimum departure time interval*

Figure 6(a), 6(b) and 6(c) are respectively the running curves under the different signaling control systems with the departure time interval of 140s. Figures display the speed and time of two trains. In figures the horizontal lines denote that the train runs with maximum speed or limited speed and from them it is obvious that in order to keep the safety stopping distance between two successive trains, the following train adjusts its speed continuously so that sometimes it accelerate and sometimes it decelerates. During the simulations, if the distance between two successive trains is smaller than the safety stopping distance, the trains will interact through the control signaling. From figures we can see that the interference of the leading train under the fixed block condition is bigger than it under the moving-like block condition and there is no interference under the moving block condition because of the appropriate departure interval. We adopt incremental method of the departure interval to get that the minimum departure time intervals are 206s under the fixed block condition, 168s under the moving-like block condition and 139s under the moving block condition. The simulation results agree with theoretical results and dynamic characteristics of the actual train flow, so it can provide references to the organizations of trains.

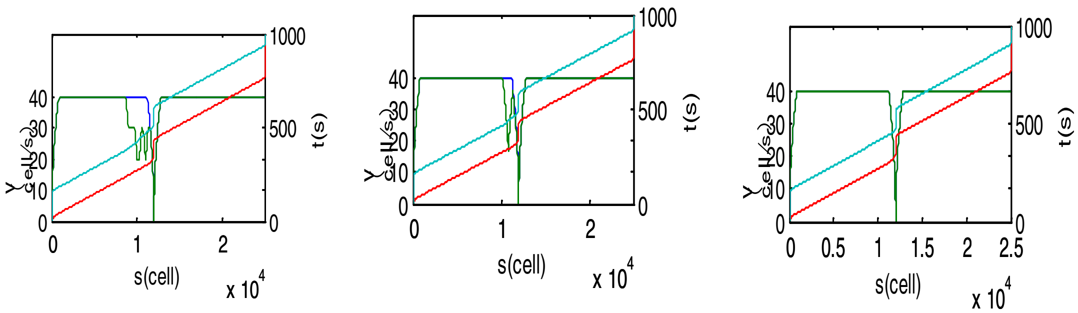



Fig. 6. (a) time diagram of fixed block system; (b) time diagram of moving-like block system; (c) time diagram of moving block system

The departure interval under different signaling systems is also directly related to the length, maximum speed, planned dwell time and the safety distance of the train and so on. Figure 7(a) shows how the departure time interval varies with the maximum speed under different signaling control systems. It is obvious that the departure time interval under the fixed block system is biggest, moving-like block system takes second place and moving block system is smallest.

*3.2.3. The analysis of the mixed train flow*

Figure 7(b) is the space-time diagrams of mixed train flow under moving block condition with the departure time interval of 135s, where the maximum speed of fast trains is 40cells/s, the maximum speed of slow trains is 20cells/s and the proportion of slow trains is 0.3. In figure7(b) the slope of the curve of the fast train is small and the slow train is big. Because overtaking is not allowed on a single rail line, inhibitory action of slow trains will make fast trains to slow down and result delay. If there is a fast train behind the delayed fast train, the delay time of following trains will increase and the delay will propagate backward. If there is a slow train behind the delayed fast train, the influence will be less and the delay time will decrease, because the minimum departure interval is considered by the train with the poor performance and the surplus of departure interval offset the delay time. If there are several consecutive slow trains, the delay will disappear gradually. From figure 7(b) we can also see the train which stay at the station after a period restart and when the fast trains which catch up the slow trains gradually slow down to keep a safe distance and it also causes the delay.

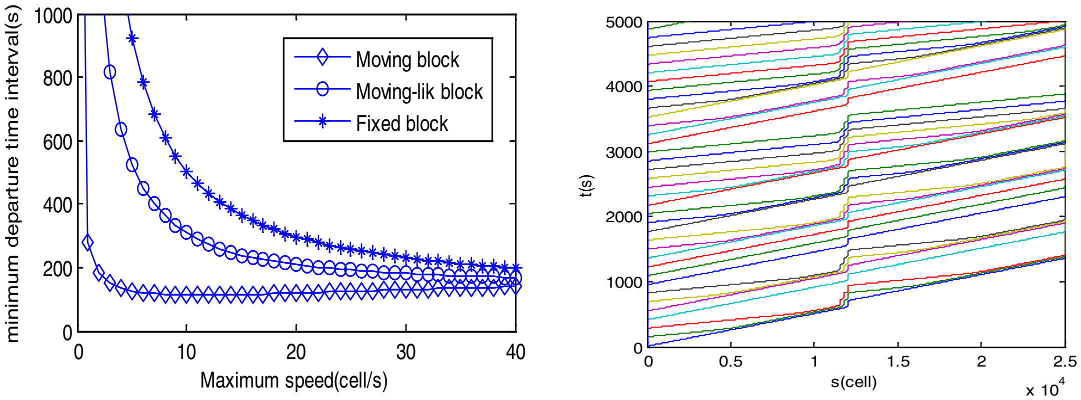



Fig. 7. (a) the departure time interval varies with the maximum speed; (b) space-time diagram of mixed train flow

Figure 8(a) and 8(b) are the space-time diagrams under moving block condition with the departure time interval of 135s when the proportion of the slow train is 0.3. Comparing these two figures, the impact of the sequence of trains on the train movement can be observed. In figure 8(a) the fast trains depart from the starting station in succession and the delays primarily form in front of station. In figure 8(b) the fast trains which depart from the starting station dispersedly can not run at full speed because of the influence of the leading slow train and the major delays form in the block section.

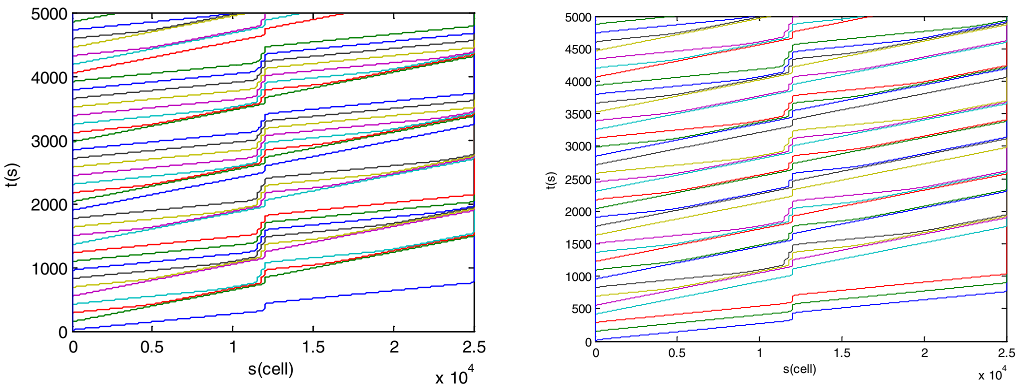


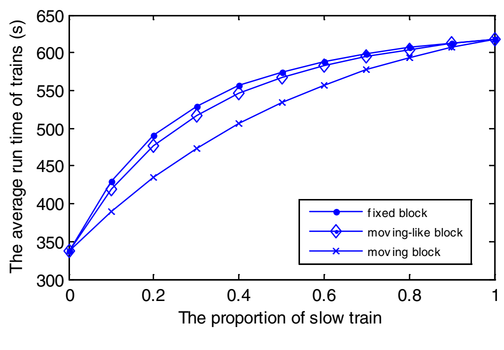

Fig. 8. (a) space-time diagram of mixed train flow; (b) space-time diagram of mixed train flow

Then we simulate mixed train movement with different proportions of slow train and the departure time interval of 210s.We implement 20000 times to get average data in order to eliminate errors and randomness. Figure 9(a) shows how the average run time of trains varies with the proportion of slow train under different signaling systems. It is obvious that the average run time of trains with the same proportion of slow train under the fixed block system is longest, moving-like block system takes second place and moving block system is shortest. As the proportion of the slow train increases, it increases. When the proportion of slow train is below 0.4, reducing the proportion of slow train will improve run time greatly.

Figure 9(b) displays average run time of trains in different departure sequences under moving block condition when the departure interval is 210s. There are twenty trains in system and the proportion of slow train is 0.3, that's to say there are six slow trains and $C_{20}^{6}$ kinds of sequences. So the number of dots in figure6 is 38760. If 1 represents fast train and 0 represents slow train, we get the shortest run time of 422s only in one kind of sequence which is 11111111111111000000 and the longest run time of 502.9s in fifteen kinds of sequences, such as 01110111011011011-011.Seclecting appropriate sequences can improve run time and the simulation can provide a reference for train operation organization.

## 4. Conclusion

In this paper, we make use of this system engineering to simulate train operation under different signaling systems and investigate the trajectory and the space-time diagram of the train flow to compare with the dynamic behaviors of actual train flow. Then we analyze the departure time interval to get the minimum departure time interval under different conditions and discuss the effect of the proportion and the departure sequence of different trains on mixed traffic flow to conclude that the minimum departure time interval and the run time under the moving block system is shortest and with the low proportion of slow train and suitable departure sequence the run time will be shorten greatly. Although numerical simulations show that the system engineering can be successfully used for the simulation of train movement, it should be pointed out that many factors which affect the train movement have not been considered, such as the track geometry, the optimal control, etc. These problems can be solved by modifying the update rules of CA model. Therefore we think it should be researched further to fit the actual railway system engineering.



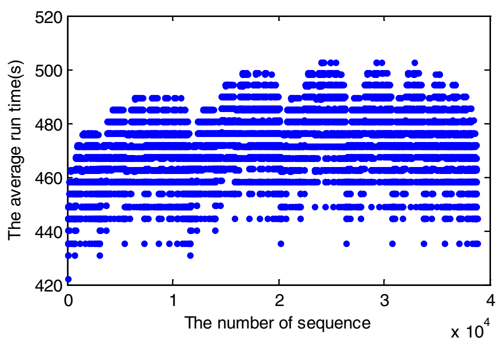




Fig. 9. (a) average run time of trains varies with the proportion of slow train; (b) average run time of trains in different departure sequences

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